Joint Centre for Mesoscale Meteorology, Reading, UK

Results of a questionnaire on the operational value of conceptual models (CMs) of fronts and cyclones

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by

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Introduction

The meteorologist has to assimilate a vast quantity of information when preparing a forecast for an individual site. This information can be derived, for example, from numerical models and observations from a variety of both surface-based and remotely-sensed sources. It is therefore necessary to have the tools to interpret this information so as to identify and rapidly assess the likely development of the important atmospheric features relevant to the sites for which forecasts (and particularly warnings of severe weather) are being prepared. CMs are a well-accepted vital tool for this purpose and form a fundamental part of the forecasting process.

A detailed definition along with a description of the role of CMs can be found in the COST-78 Phase 1 report. However, for the purpose of this report it can be stated that CMs are effectively a representation of complex physical and dynamical atmospheric processes ideally within a simple, flexible framework. They provide a means to relate observed or anticipated weather conditions to atmospheric phenomena of various scales. Furthermore they assist the meteorologist in comparing numerical model guidance against observations and thereby to identify errors and so make appropriate adjustments to the numerical model forecasts.

Many different conceptual models are used in forecasting centres around Europe, but little attempt has been made so far to assess the usefulness of such models on a day-to-day basis. A two-stage approach was adopted to address this problem. The first stage, which has been completed and presented in the Phase 1 Report, was to assess the current status of conceptual models used in nowcasting in Europe and to bring together all known conceptual models. The next step, identified in the Proceedings of the Bologna Workshop, was to assess just how useful these models are perceived to be by the forecasting community. With this in mind, a survey has been carried out amongst the participating COST-78 members, the results of which are presented below.

The remaining content of this report will be split in the following way

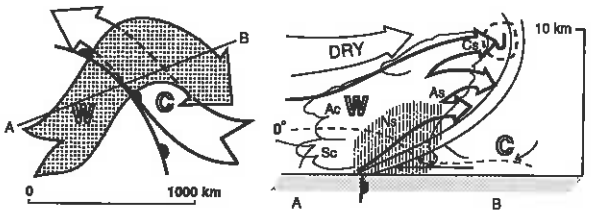
1) A concise description of each of the CMs used in the questionnaire.
2) The questions that were asked about each of the conceptual models.
3) Results from the questionnaire.
4) Final discussion and recommendations.

1) The conceptual models

Questions were asked about 28 CMs of fronts and cyclones. The CMs were selected from the much larger sample presented in the Phase I report to represent a balance between long-established and more recently developed models. These models are described below in figures 1(a) to 1(e). The descriptions

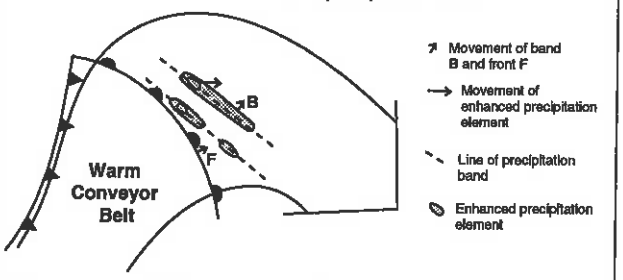
used in the questionnaire were essentially the same as shown here, although in the questionnaire they were not compressed into this six per page format. The aim was to present the CMs in a way that would allow instant recognition, but not expand into too much detail.

1 Classical warm front



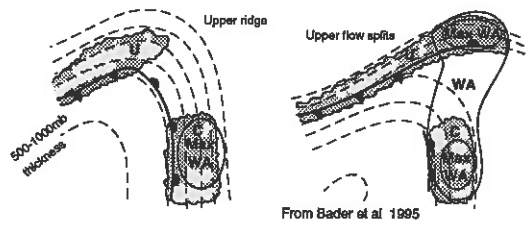
Ascending warm conveyor belt giving rise to cloud shield and precipitation mainly ahead of the surface front. Cold conveyor belt is descending some distance ahead of the front, but ascending immediatley ahead of and parallel to the surface front. In terms of quasigeostrophic thinking - the ascent is mainly associated with warm advection, but also positive vorticity advection aloft near the cyclone centre. The positions of surface warm fronts are not easy to identify using satellite imagery.

2 Warm front substructure: precipitation bands



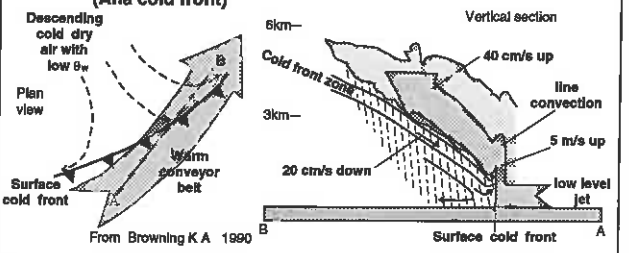
Enhanced precipitation bands within the warm frontal surface. Investigations using radar and thermodynamic data suggest that the bands may be associated with conditional symmetric instability (CSI). Bands are typically 50km wide and a few hundred kilometres long. They are usually oriented at a small angle to the front. Bands/rolls move faster than the surface front. They rise and eventually the precipitation dies out.

3 Warm front subtype: detached warm front



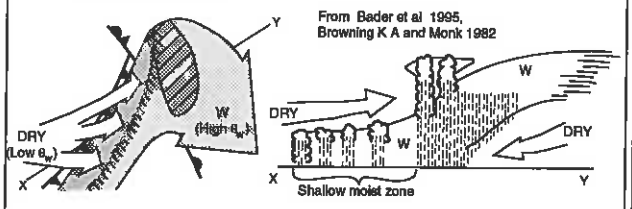
Sometimes warm frontal cloud may appear completely detached from other areas ofcloud - there may be a separate cloud area C downwind of an upper thickness ridge. If the upper pattern splits and the flow in both branches is strong, a detached cloud area C may exist in the equatorward branch. The cloud C may appear in an area of warm advection (WA) remote from, and downstream of, any other WA maximum. Cloud often appears bright in visible images and cold in infrared, showing that the frontal zone extends through a deep layer of the troposphere.

4 Cold front with rearward-sloping warm conveyor belt (Ana cold front)



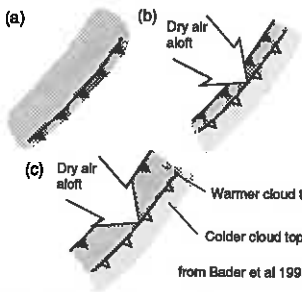
Schematic diagrams are in a system relative frame. Warm conveyor belt (bold arrow) undergoes rearward sloping ascent above the cold frontal zone. Cold dry air (dashed lines) descends beneath the cold frontal zone. A narrow cold frontal rainband or line convection may occur at the surface front.
A wider stratiform rain area occurs behind the surface front. This may consist of multiple rainbands.

5 Cold front with forward-sloping warm conveyor belt (split (kata) front)

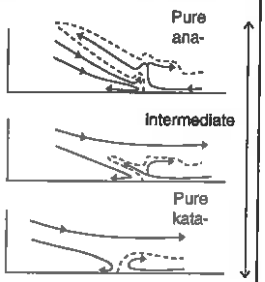


Warm conveyor belt is overrun aloft by dry air as the warm air ascends ahead of the surface cold front with a component forward relative to the frontal system. Deepest cloud and rainfall lies ahead of the surface cold front. Aloft, the leading edge of the dry air is called an upper cold front (or upper humidity front). A shallow moist zone is created between the upper front and surface cold front. If dynamical forcing is strong enough, release of potential instability may lead to deep convection through the shallow moist zone.

6 Split-front evolution
Transition from rearward-sloping to forward-sloping type



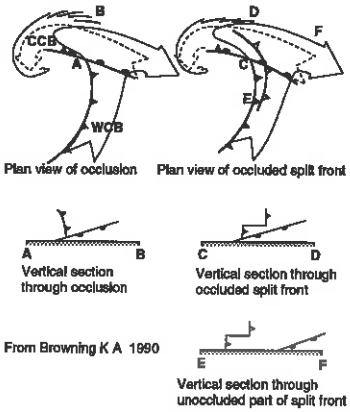
Schematics showing transition as seen in IR, from a single classical frontal cloud band to a split frontal band as dry air overruns aloft.



Schematic cross-sectional representations of the spectrum of cold front types. from Browning K A 1995

Figure 1(a)

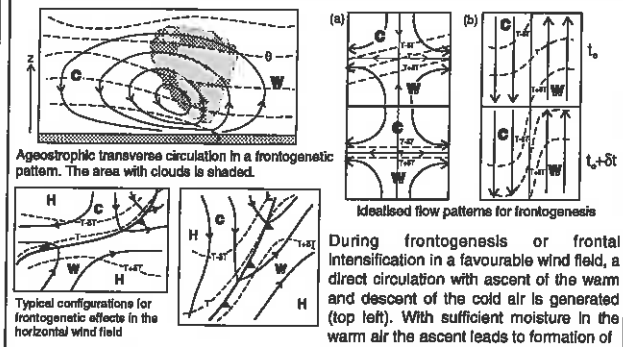
7 Classical occlusion



Air within the warm conveyor belt (WCB) ascends above the cold conveyor belt (CCB), with no sign of warm air at the surface. Associated with maturing cyclonic circulation. Cloud bands of the WCB and CCB are often distinct from each other in satellite imagery.

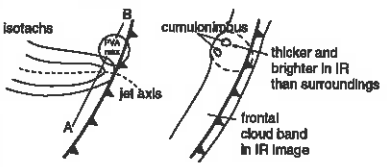
The occlusion may resemble a split front if an upper cold front overruns the WCB and leaves a shallow moist layer below the overrunning cold air and above the CCB air at the surface.

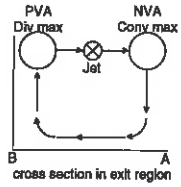
8 Direct transverse circulation around fronts in the case of frontogenesis in the horizontal wind field or due to diabatic effects

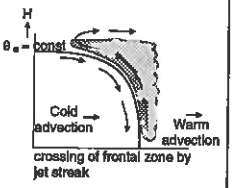


During frontogenesis or frontal intensification in a favourable wind field, a direct circulation with ascent of the warm and descent of the cold air is generated (top left). With sufficient moisture in the warm air the ascent leads to formation of cloud and precipitation bands. A diagnosis of vertical motion can be performed by comparison of the evolution of streamlines and isotherms, or more objectively with the aid of Q-vector diagnostics.

9 Intensification of frontal activity in the left exit region of jet streaks



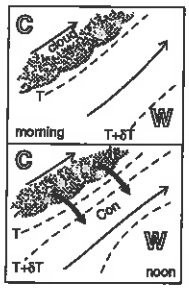




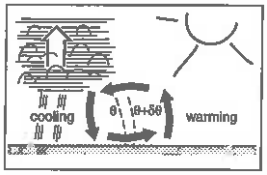
If a jet streak approaches and crosses a frontal zone at a large angle, cloudiness and precipitation are enhanced at the left exit region of the jet streak. Often deep convection is embedded. Key diagnostics for identifying such an event are - some way of locating the front, isotachs and vorticity advection. IR imagery shows developing cloud. WV imagery can be useful for identifying the jet streak and any upper-level vorticity maximum.

Zwatz-Meise V and G Mahringer 1990

10 Development of shallow front lines at the edge of cloud and precipitation areas

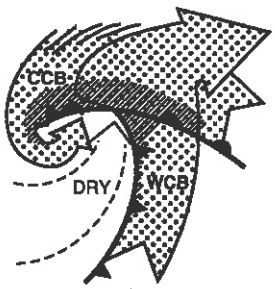


From Kurz M 1984



Large temperature differences over land at the edge of extensive cloud and precipitation areas in summer. Shallow circulation is established perpendicular to the cloud edge. A convergence line with a temperature discontinuity can develop within a few hours. If the lapse rate of the warm air is potentially unstable, convective clouds may develop. The new frontal boundary may transform into a squall line.

11 Two moist conveyor-belt (Carlson) model

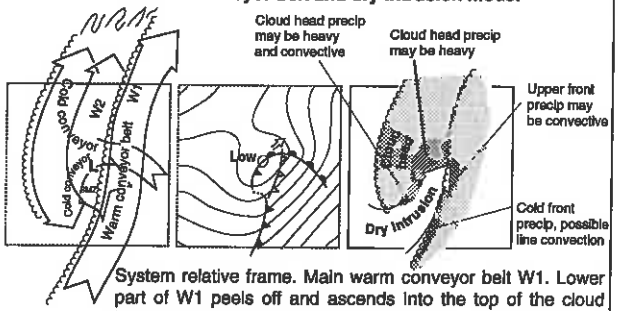


Reproduced from Young M V, Weather 49.

Ascending warm conveyor belt (WCB) produces a large area of cloud and precipitation. At higher levels the WCB turns to the right and carries high cloud well ahead of the developing cyclone.Cold conveyor-belt (CCB) originates at low levels ahead of the warm front and beneath the WCB and moves towards and around the cyclone centre. Seen on satellite imagery as much warmer (lower) clouds circulating around the low ahead of the occlusion.

Descending tongue of dry air (dry intrusion), partially of stratospheric origin, originates from upstream, and can be seen as a dark region on WV imagery.

12 Three moist conveyor-belt and dry intrusion model

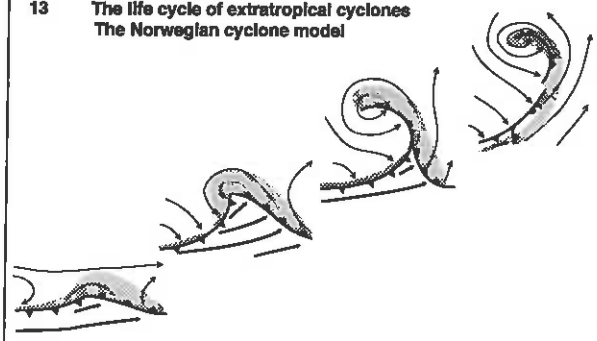


From Browning K A 1995

System relative frame. Main warm conveyor belt W1. Lower part of W1 peels off and ascends into the top of the cloud head as W2. Cold conveyor belt beneath W1 and W2 is responsible for a large part of the cloud head. Dry intrusion flow towards the cyclone centre. Possible cold frontal fracture near low centre, with an upper cold front developing. Convection likely in the vicinity of the dry intrusion due to the release of potential instability.

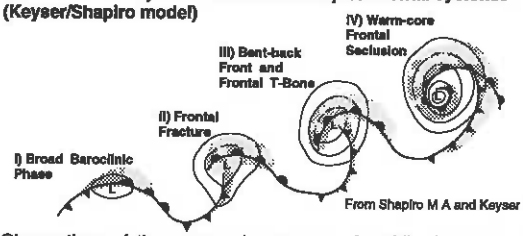
Figure 1(b)

13 **The life cycle of extratropical cyclones**
The Norwegian cyclone model



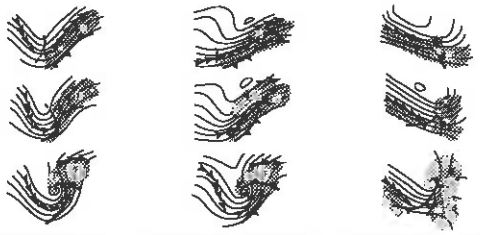
Successive stages of development of a frontal wave to an occluded vortex

14 **The life cycle of marine extratropical frontal cyclones (Keyser/Shapiro model)**



Observations of the mesoscale structure of rapidly deepening marine cyclones have shown that the frontal zone temperature gradient at which the cyclones originate undergoes typical changes. **Phase I** Continuous and broad frontal zone (~400km across). **Phase II** Gradient weakens at cold front near the centre and increases further along the cold front (frontal fracture). Warm front gradient and gradient around low increases. **Phase III** Area with strong gradient extends to the rear of the cyclone - bent back warm front. **Phase IV** Bent back warm front extends around the centre of the cyclone leading to a seclusion of warm air in the centre.

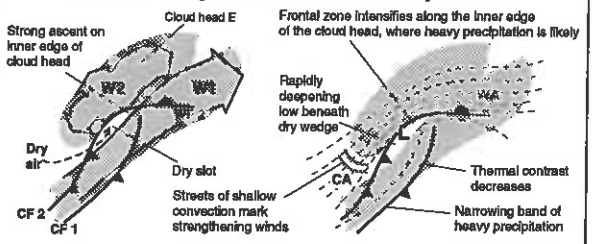
15 **Cyclogenesis life-cycles**



(a) Meridional trough (b) Flat trough confluent flow (c) Flat trough diffluent flow

The evolution of the cloud features is largely determined by the shape of the upper-air pattern. The principal mid/upper cloud features comprise F - associated with the main frontal zone and E - new layered cloud appearing during cyclogenesis.
(a) Meridional trough - often evolves into the two moist conveyor-belt model of Carlson (model 11)
(b) Flat trough, confluent flow - sometimes associated with 'cloud head' development and explosive cyclogenesis (model 16)
(c) Flat trough diffluent flow - area E becomes elongated normal to the upper flow - often associated with split-front development (model 5)

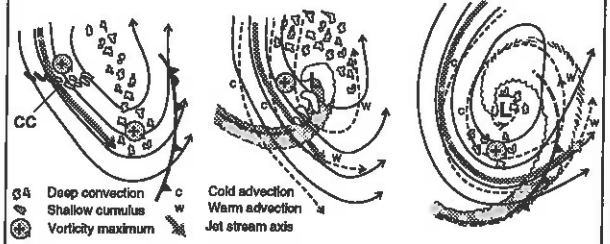
16 **Explosive cyclogenesis: Cloud head and dry slot**



This cloud signature is usually followed by explosive cyclogenesis. Cloud head (leaf) **E** composed of rapidly ascending warm conveyor belt **W2** is seen in imagery to be particularly broad and 'leaf shaped' with a sharp convex poleward boundary. A pronounced and narrow 'dark zone' or 'dry slot' or 'dry intrusion' separates the cloud head from the polar front cloud band associated with **W1**. This dry slot is usually associated with a tongue of stratospheric air, recently descended into the troposphere which has high values of potential vorticity.

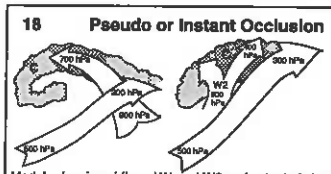
From Bader et al 1995

17 **Comma-cloud system** Based on Reed and Biller 1986



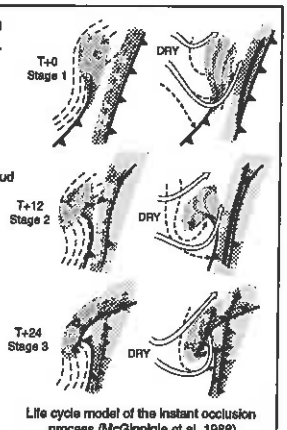
A comma-shaped cloud area **CC** forms in a region of positive vorticity advection (PVA) within a cold, conditionally unstable airmass. A cluster of initially discrete convective elements merge to form a layered cloud canopy. Precipitation often takes the form of deep convection well into the life-cycle. The bulk of the precipitation lies along the rear edge. There is often no discrete surface low centre, just one or more troughs. If the upper-level forcing persists, the comma-cloud can undergo significant cyclogenesis, eventually acquiring baroclinic characteristics.

18 **Pseudo or Instant Occlusion**



Models showing airflows W1 and W2 and extent of cloud area C in two configurations of an instant occlusion. (McGinnigle, Young and Bader 1988)

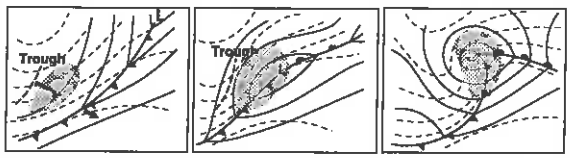
Cyclogenesis occurs when an expanding layered or convective cloud region associated with a polar air trough (**C** in life cycle figures to the right) approaches and interacts with a cloud band associated with a pre-existing frontal zone. The cloud pattern can end up resembling a classical occlusion of a maturing depression, but the cloud pattern does not evolve via the classical occluding process.



Life cycle model of the instant occlusion process (McGinnigle et al. 1988)

Figure 1(c)

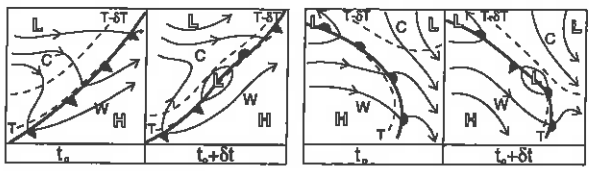
19 Cyclogenesis due to superposition of an upper vorticity maximum (Petterssen scheme)



Shading shows the region of appreciable positive vorticity advection (PVA) aloft Petterssen S 1956

Cyclogenesis can be expected where and when an upper vorticity maximum (e.g. within a cold upper trough or at the cyclonic flank of a jet-streak) approaches and engages a slower moving frontal trough or frontal wave in the lower troposphere. A coupled system with a backward tilted trough axis can develop. The movement of the upper vorticity maximum can often be seen in satellite imagery - either from cloud associated with the vorticity maximum itself or from dark (dry) regions in water vapour imagery.

20 Wave development in a frontogenetic pattern



Wave development at a cold front

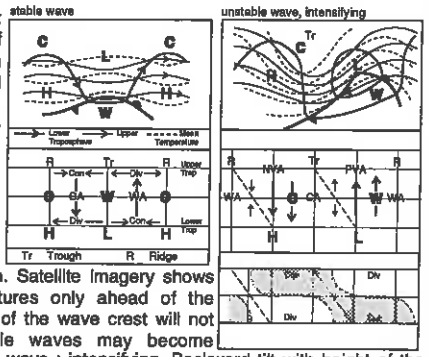
Wave development at a warm front

From Kurz M 1992

Transverse circulation produced by frontogenesis in the horizontal wind field causes pressure fall, convergence and production of cyclonic vorticity. Q-vector diagnostic is particularly well suited to diagnosing this type of wave development. The wave may grow if the stretching deformation along the frontal zone from the large scale flow pattern is not too strong - or if other cyclogenetic effects are induced from upper levels.

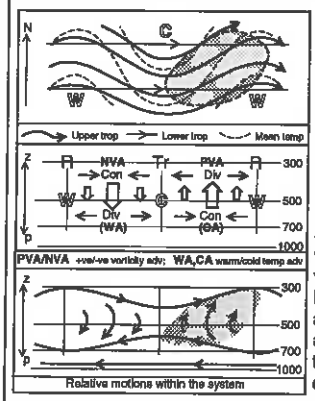
21 Stable and unstable baroclinic waves

From Kurz M 1990
Holton J R 1972



(1) Stable wave : Phase difference of 180 degrees between geopotential and temperature. Warmest air in the wave trough and coldest in the flanking ridges. Trough axis is upright and the wave is often shallow, fast moving, with a short wavelength < 2000km. Satellite imagery shows significant cloud features only ahead of the trough. The pressure of the wave crest will not change much. Stable waves may become unstable. (2) Unstable wave : intensifying. Backward tilt with height of the vertical axis of the wave trough. Satellite imagery shows significant cloud ahead and in the centre and to the rear. Trough axis eventually tilts unright.

22 Upper baroclinic waves (Short wave upper troughs)

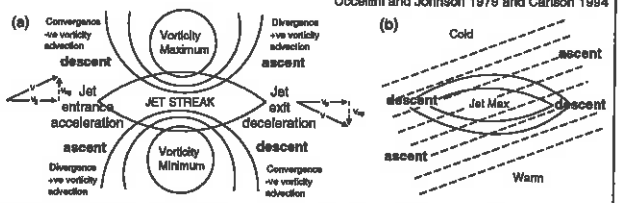


From Kurz M 1987

Short baroclinic waves (wavelength < 2000km) with cold troughs and warm ridges. They are often confined to levels above 700 hPa and show their greatest amplitude near the jet stream level. The waves move in the direction and with the speed of the basic flow at 400-500 hPa. They may be associated with significant precipitation but little surface pressure signature. The dynamics of these waves are mainly determined by vertically increasing vorticity advection leading to ascent ahead of the trough and descent at the rear. The ascent ahead of the trough usually leads to the formation of cloud (partly comma or spiral-like) which may be convective in nature.

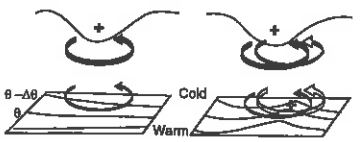
23 Straightline jet streak models - and associated vertical motion

Uccellini and Johnson 1979 and Carlson 1994



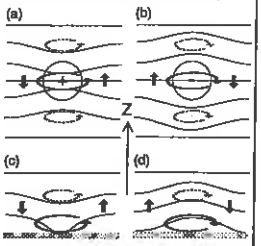
(a) Straight line jet streak in which isentropes are (nearly) parallel to streamlines, with cold air on the left (cyclonic) side, warm air on the right (anticyclonic) side. Ageostrophic wind components due to acceleration at the jet entrance and deceleration at the jet exit leads to a pattern of upper-level convergence at the left entrance and right exit and upper-level divergence at the right entrance and left exit. The right entrance and left exit are favoured regions for mid-level ascent, increased cloudiness and possible cyclogenesis. (b) Like (a) but the isentropes are not parallel to the jet axis (also not perpendicular). The ascent/descent pattern is shifted as shown. Tropopause folding can occur in this case of cold air advection.

24 Cyclogenesis using the concept of Potential Vorticity (PV)



Schematic picture of cyclogenesis associated with the arrival of an upper-level positive PV anomaly over a low-level baroclinic region. The circulation associated with the upper-level PV anomaly is indicated by the solid arrows. The advection by the circulation leads to a warm temperature anomaly ahead of the PV anomaly. This warm anomaly induces the cyclonic circulation indicated by the open arrows. (From Hoskins et al 1985)

The atmosphere can be thought of as consisting of a superposition of positive and negative PV anomalies. Maps showing PV on isentropic surfaces are most commonly used, since PV is conserved on an isentropic surface.



The isentropes and circulation for idealised positive (a) and negative (b) PV anomalies, and for warm (c) and cold (d) surface temperature anomalies. Arrows show the sense of the vertical motion if there is a basic flow along the sections which increases with height. (From Hoskins 1997, Hoskins et al 1985, Thorpe 1985, Hoskins and Berrisford 1988)

Figure 1(d)

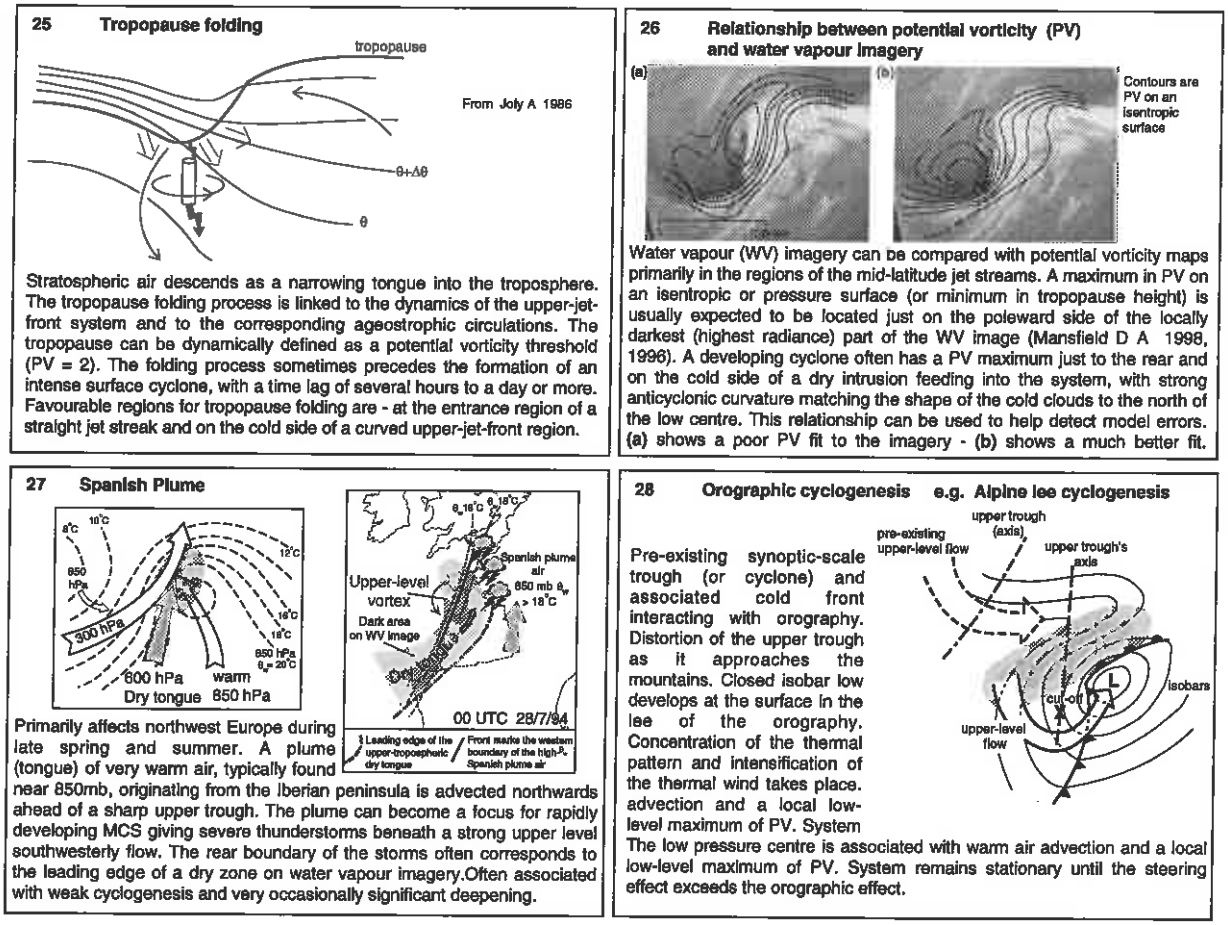


Figure 1(e)

2) The questions asked about each of the CMs

Figure 2 contains the questions that were asked about each of the CMs in the format they appeared in the questionnaire.

3) Results

126 completed questionnaires were received from 13 European countries. The number of replies from each country is shown in table 1. The distribution of replies is well balanced in that no single country dominates. However, only a few questionnaires were completed by forecasters from Alpine or Mediterranean countries. Geographical distribution becomes significant when assessing the results for conceptual models that are specifically designed to apply to particular regions. Table 1 also shows, in four categories, the number of years respondents had spent in forecasting (if they replied to this question) - indicating a broad spread of experience.

Q1. Have you come across this conceptual model / theory? Please tick one box

☐ Yes ☐ Possibly ☐ No

If you answered 'Yes' or 'Possibly' to question 1 please answer questions 2, 3 and 4, otherwise go to the next page.

Q2. Do you ever use your knowledge of this conceptual model / theory in the day to day forecasting environment?

☐ Yes as often as applicable
☐ Yes sometimes when applicable
☐ Yes once or twice ever
☐ No

Please tick one box

Q3. Do you find that your knowledge of this conceptual model has been useful in the day to day forecasting environment?

☐ Yes extremely useful
☐ Yes quite useful
☐ Maybe / not sure
☐ No

Please tick one box

Q4. What reservations, if any, would you have about applying knowledge of this conceptual model to forecasting? Please tick any number of boxes.

☐ I don't think it is sufficiently correct
☐ It does not help my understanding of this type of situation
☐ I don't have the information/diagnostics available to use this model
☐ It does not add any extra value to the numerical model output I have available
☐ I don't understand this conceptual model well enough
☐ Other conceptual models/ methods are better suited to this type of situation
☐ Other - please comment

Figure 2

3.1) Knowledge of the conceptual models (figure 3(a))

It is important firstly to establish how many of the forecasters have come across each of the CMs before going on to discover if the CMs are useful or not. The replies to the question 'Have you come across this conceptual model/theory?' are shown in figure 3(a). The black bars on the graph show the percentage of those who replied 'Yes' or 'Possibly'. As might be expected, the more traditional (i.e. long established) models such as the 'Norwegian cyclone model' and the 'Classical warm front' are the best known. It is suprising how many forecasters have not come across some of these CMs. Only 10 of the 28 CMs have been encountered by more than 60% of respondents and only 3 of the 28 by more than 80% of respondents.

If the percentage of forecasters who have come across and understand these CMs is examined (grey bars), then only 6 of the 28 CMs score 60% and just 2 of the 28 score 80%.

There is obviously a difference between just knowing about a CM and understanding it. This gap in understanding varies between CMs, it is small for the best known more traditional models such as the 'Norwegian cyclone model' and largest for the CMs that involve more complex dynamical concepts such as Q-vectors and potential vorticity (PV).

Country	Number of replies	0-5 years experience	6-10 years experience	11-20 years experience	> 21 years experience
Belgium	4	1	1	2	
Czech Republic	1		1		
Finland	8	2	3	2	
France	17	1	5	11	
Germany	17	5	2	6	3
Greece	6			6	
Netherlands	5			4	1
Norway	10	Average of 10 years			
Portugal	8	4	3	1	
Slovenia	11	6	1	4	
Sweden	18		4	3	8
Switzerland	4	1	1	1	1
UK	19	2	3	9	5
Total	126	22 19.5%	24 21.2%	49 43.4%	18 15.9%

Table 1

3.2) Use of the conceptual models (figure 3(b))

Figure 3(b) shows the percentage of respondents who answered 'Yes as often as applicable' or 'Yes sometimes when applicable' to the question 'Do you ever use your knowledge of this conceptual model/theory in the day to day forecasting environment?' A good proportion, (20 out of 28), of the CMs are used by more than 50% of the forecasters who know about them. In general the most used CMs are also the best known. Notable exceptions to this rule are the PV based models and the 'Warm front bands' model. They are comparatively less often used, which may be because they are less well understood, but there could be other factors. The 'Spanish plume' and 'Cyclogenesis life cycles' models are exceptions in the opposite sense, they are often used by the relatively few that know about them.

3.3) Usefulness of the conceptual models (figures 3(c) & 3(d))

We need to know how useful CMs are perceived to be by the forecasters that are exposed to them, in order to assess the current value of CMs in the forecasting environment. Figure 3(c) shows the percentage of respondents who answered 'Yes extremely useful' or 'Yes quite useful' to the question 'Do you find that your knowledge of this conceptual model has been useful in the day to day forecasting environment?' It appears that many forecasters do find these CMs useful, with 22 out of the 28 CMs considered to be useful by more than 50% of the respondents who know about them; although only 4 of the 28 CMs register more than 70%. It is immediately apparent that there is a strong correlation between the use and usefulness of the CMs (figure 3(d)). The most used, such as the 'Norwegian cyclone model', 'Classical warm front', 'Ana cold front', 'Comma cloud' and 'Petterssen vorticity' are also regarded as the most useful. The least used, such as the 'Three-conveyor belt model', 'Detached warm front', 'PV and cyclogenesis' and 'Tropopause folding' are also registered as the least useful. This is not suprising, as forecasters are unlikely to use a CM they consider not to be useful and are not going to find a CM useful that they don't use. Familiarity apparently plays an important part in the perceived usefulness. On the other hand, there are CMs that depart somewhat from this general rule, i.e. the 'Classical occlusion' is the 4th most used yet the 15th most useful and in the opposite sense the 'Fronts at cloud edges' model is the 21st most used but the 11th most useful.

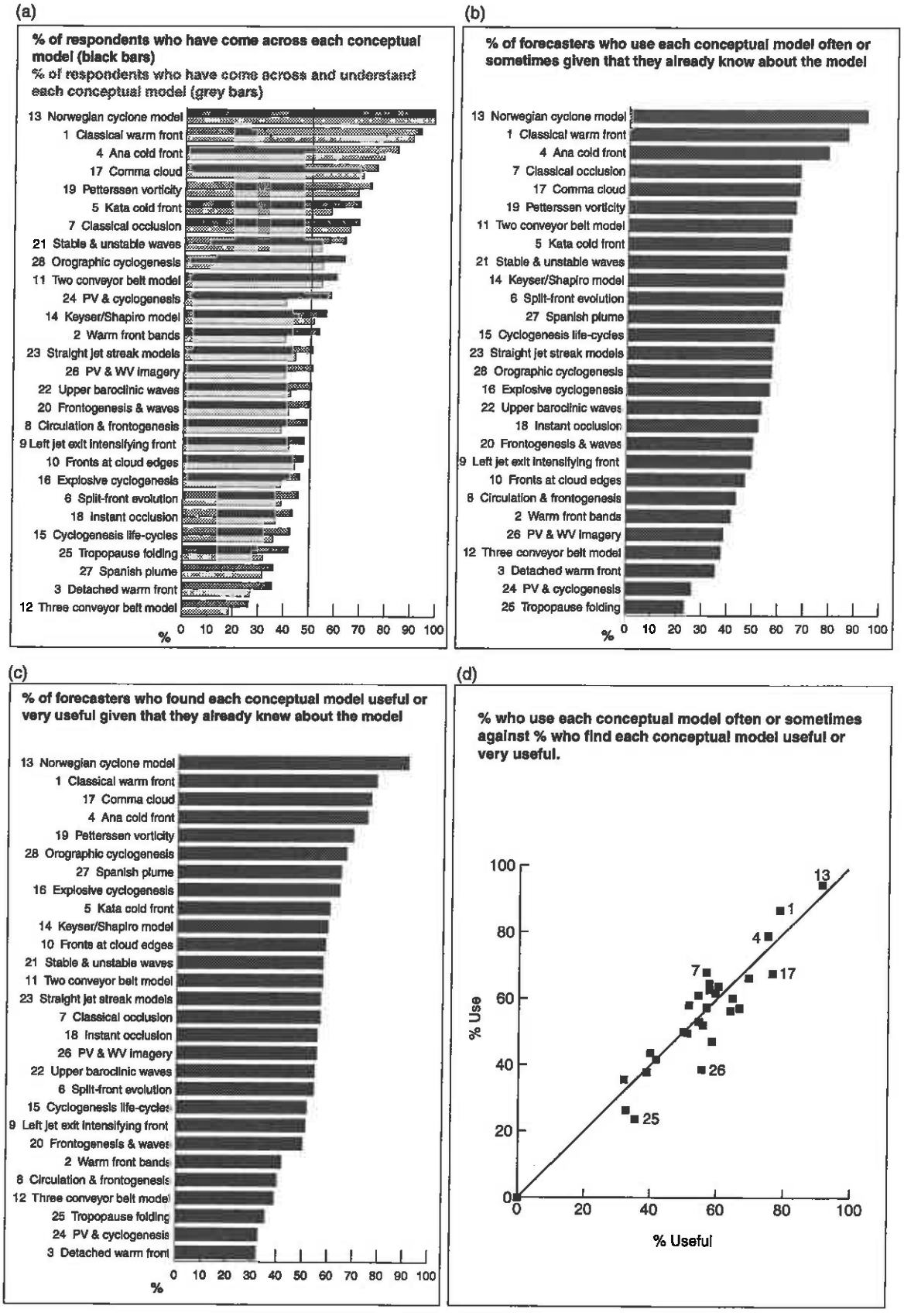

(a)
% of respondents who have come across each conceptual model (black bars)
% of respondents who have come across and understand each conceptual model (grey bars)
13 Norwegian cyclone model
1 Classical warm front
4 Ana cold front
17 Comma cloud
19 Petterssen vorticity
5 Kata cold front
7 Classical occlusion
21 Stable & unstable waves
28 Orographic cyclogenesis
11 Two conveyor belt model
24 PV & cyclogenesis
14 Keyser/Shapiro model
2 Warm front bands
23 Straight jet streak models
26 PV & WV imagery
22 Upper baroclinic waves
20 Frontogenesis & waves
8 Circulation & frontogenesis
9 Left jet exit intensifying front
10 Fronts at cloud edges
16 Explosive cyclogenesis
6 Split-front evolution
18 Instant occlusion
15 Cyclogenesis life-cycles
25 Tropopause folding
27 Spanish plume
3 Detached warm front
12 Three conveyor belt model
% 0 10 20 30 40 50 60 70 80 90 100
(b)
% of forecasters who use each conceptual model often or sometimes given that they already know about the model
13 Norwegian cyclone model
1 Classical warm front
4 Ana cold front
7 Classical occlusion
17 Comma cloud
19 Petterssen vorticity
11 Two conveyor belt model
5 Kata cold front
21 Stable & unstable waves
14 Keyser/Shapiro model
6 Split-front evolution
27 Spanish plume
15 Cyclogenesis life-cycles
23 Straight jet streak models
28 Orographic cyclogenesis
16 Explosive cyclogenesis
22 Upper baroclinic waves
18 Instant occlusion
20 Frontogenesis & waves
9 Left jet exit intensifying front
10 Fronts at cloud edges
8 Circulation & frontogenesis
2 Warm front bands
26 PV & WV imagery
12 Three conveyor belt model
3 Detached warm front
24 PV & cyclogenesis
25 Tropopause folding
% 0 10 20 30 40 50 60 70 80 90 100
(c)
% of forecasters who found each conceptual model useful or very useful given that they already knew about the model
13 Norwegian cyclone model
1 Classical warm front
17 Comma cloud
4 Ana cold front
19 Petterssen vorticity
28 Orographic cyclogenesis
27 Spanish plume
16 Explosive cyclogenesis
5 Kata cold front
14 Keyser/Shapiro model
10 Fronts at cloud edges
21 Stable & unstable waves
11 Two conveyor belt model
23 Straight jet streak models
7 Classical occlusion
18 Instant occlusion
26 PV & WV imagery
22 Upper baroclinic waves
6 Split-front evolution
15 Cyclogenesis life-cycles
9 Left jet exit intensifying front
20 Frontogenesis & waves
2 Warm front bands
8 Circulation & frontogenesis
12 Three conveyor belt model
25 Tropopause folding
24 PV & cyclogenesis
3 Detached warm front
% 0 10 20 30 40 50 60 70 80 90 100
(d)
% who use each conceptual model often or sometimes against % who find each conceptual model useful or very useful.
% Use
% Useful
0 20 40 60 80 100
13
1
4
17
7
26
25

Figure 3

These departures are interesting because they say something about how useful a CM is in comparison to how much it is used. In other words, it is possible that a CM may be little known about, little used, but regarded as useful by those that do use it; or a CM may be well known about, well used, but a smaller proportion of those that use it may find it useful. The graph in figure 3(d) shows the relationship between use and usefulness. The CMs furthest to the left of the line are the least useful in comparison to usage and the CMs to the right of the line are the most useful in comparison to usage. This approach of examining the departures from the line will be used later and possible pitfalls involved associated with this method will be mentioned.

3.4) National dependence (figure 4)

The CMs used in this questionnaire have been developed in many different countries. It might therefore be a possibility that forecasters from the country where a particular CM was developed or advanced will be more familiar with and use that CM more than forecasters from elsewhere. Such a national dependence is not apparent for the most well known CMs, but is very evident for some of the less well-known ones. The graphs in figure 4 highlight this national dependence for three of the less well-known models by showing the replies to questionnaire questions 1,2 and 3 from respondents in the country involved in the model development separately from the other respondents. The differences are very marked and indicate that there may be a problem in communication of new CMs between countries. Other models could have been chosen to demonstrate the same differences. It should be noted that some of these differences are also because some CMs are designed for particular geographical regions, e.g. The 'Spanish plume' model is not intended to be useful in Greece.

3.5) Understanding of the CMs (figure 5(a))

Generally, forecasters have most confidence in their understanding of the most used models. All forecasters feel that they understand the 'Norwegian cyclone model'. The 'Fronts at cloud edges' model stands out as being well understood even though it is one of the least used. The least understood CMs are mostly to do with PV and frontal substructure. No single CM stands out as being less well understood than the rest.

3.6) Correctness of the CMs (figure 5(b))

The 'Classical warm front' and the Norwegian cyclone model' stand out dramatically as being regarded as the least correct. They may be the most criticised because they are the most well known, understood and used, giving ample opportunity to reveal their weakness. By contrast, the 'Ana cold front', 'Kata cold front', 'Comma cloud' and 'Petterssen vorticity' models are well known and used but not criticised much. There is suprisingly little concern about the correctness of most of the CMs. This may be because the forecasters do not have enough confidence in their understanding or enough experience in using the models to be critical, or it may be that the CMs do accurately represent the atmospheric phenomena they are supposed to. The complete lack of criticism of the correctness of the 'PV & WV imagery' model must reflect a lack of understanding of this model, since this is a relationship that is not properly understood within the research community.

3.7) Availability of diagnostics (figure 5(c))

The distribution is split broadly into three clusters, which are labelled A.B and C on the bar chart in figure 5(c).

Cluster A: Least problem with availability of diagnostics. Most of the models describe the larger synoptic scales and cyclones. These are the scales that NWP forecast models handle best. The typical set of diagnostics that are extracted from NWP models is adequate to describe these features.

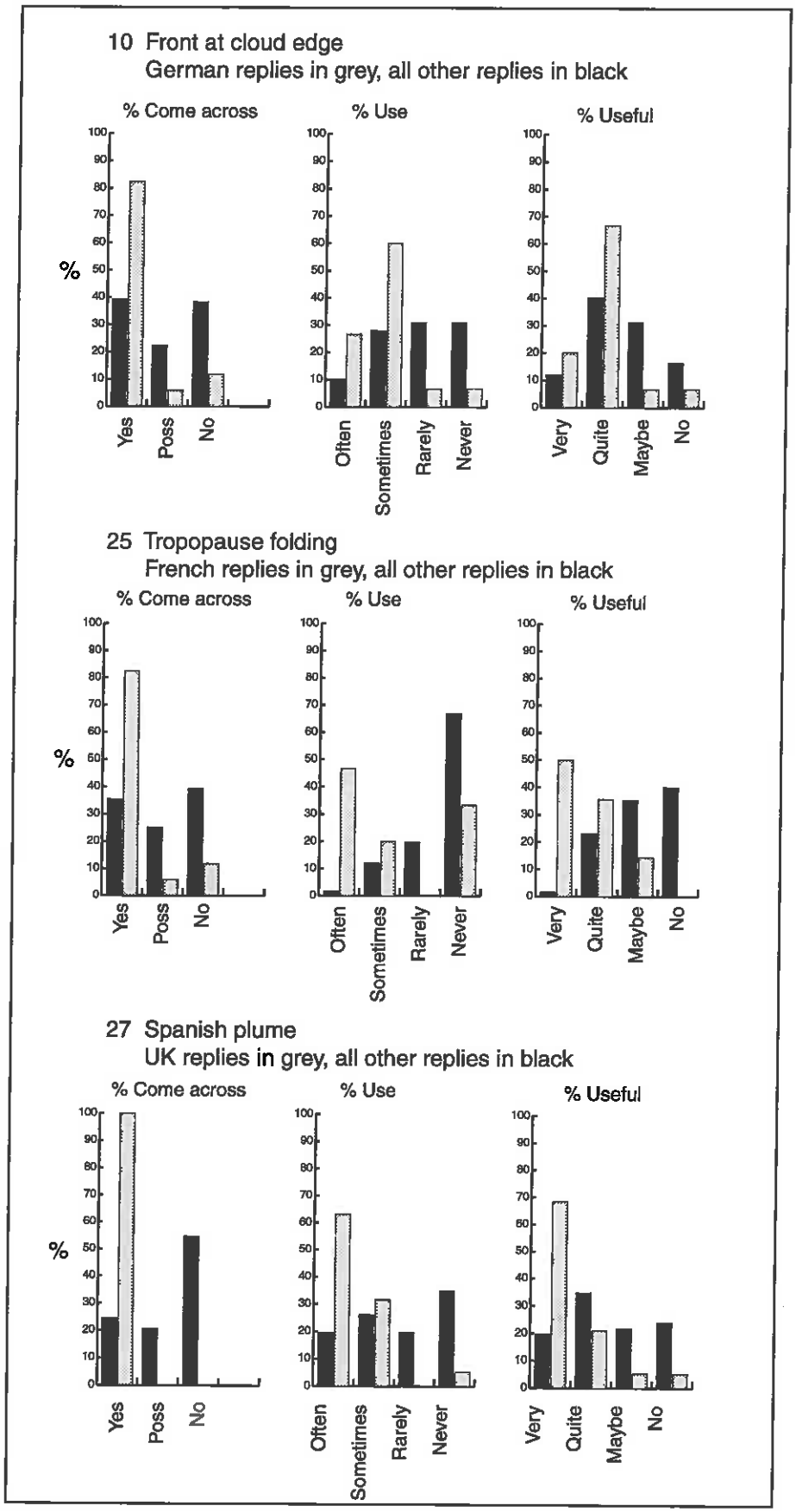

10 Front at cloud edge
German replies in grey, all other replies in black
% Come across
% Use
% Useful
%
Yes
Poss
No
Often
Sometimes
Rarely
Never
Very
Quite
Maybe
No
25 Tropopause folding
French replies in grey, all other replies in black
% Come across
% Use
% Useful
%
Yes
Poss
No
Often
Sometimes
Rarely
Never
Very
Quite
Maybe
No
27 Spanish plume
UK replies in grey, all other replies in black
% Come across
% Use
% Useful
%
Yes
Poss
No
Often
Sometimes
Rarely
Never
Very
Quite
Maybe
No

Figure 4

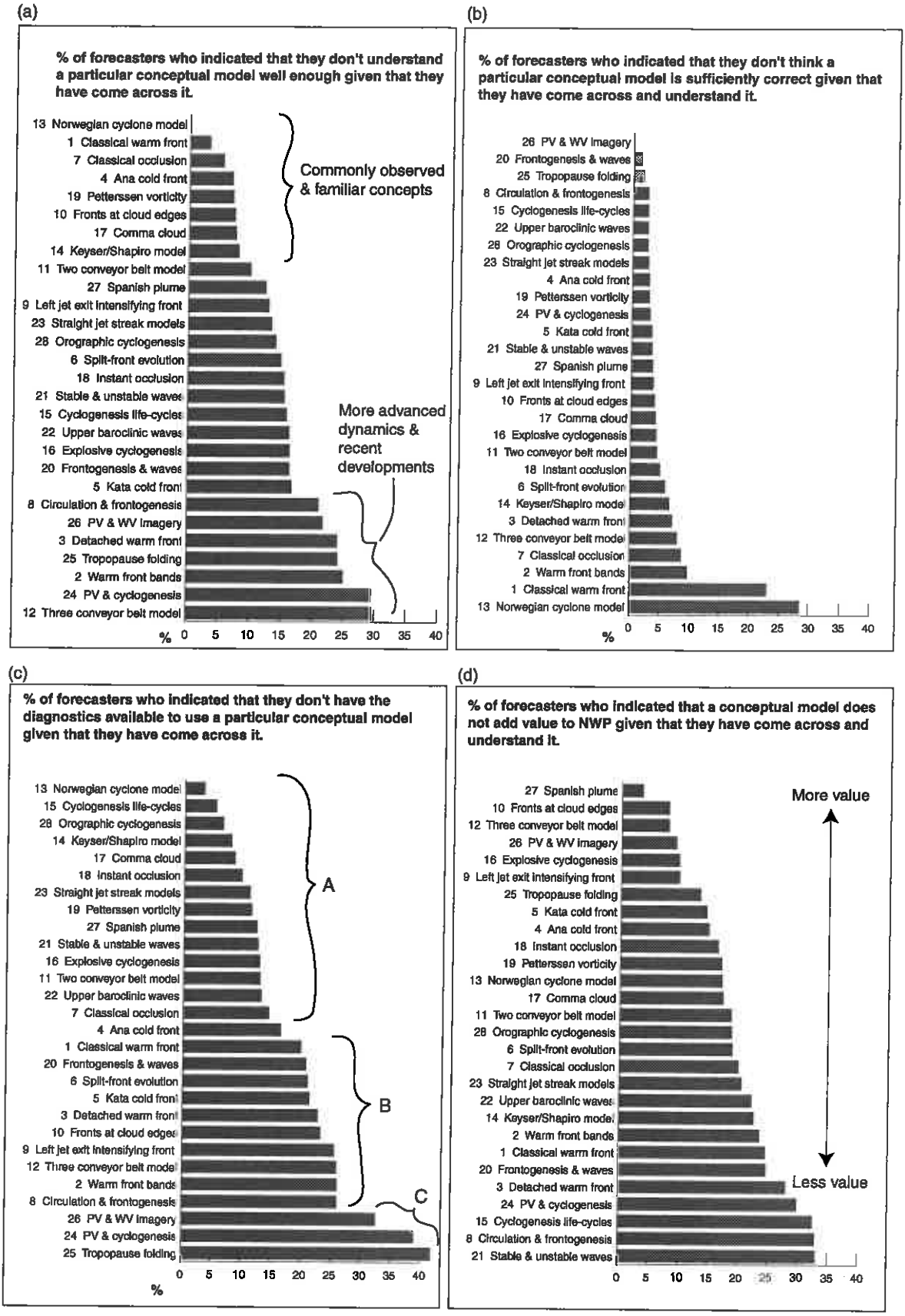

(a)
% of forecasters who indicated that they don't understand a particular conceptual model well enough given that they have come across it.
13 Norwegian cyclone model
1 Classical warm front
7 Classical occlusion
4 Ana cold front
19 Petterssen vorticity
10 Fronts at cloud edges
17 Comma cloud
14 Keyser/Shapiro model
11 Two conveyor belt model
27 Spanish plume
9 Left jet exit intensifying front
23 Straight jet streak models
28 Orographic cyclogenesis
6 Split-front evolution
18 Instant occlusion
21 Stable & unstable waves
15 Cyclogenesis life-cycles
22 Upper baroclinic waves
16 Explosive cyclogenesis
20 Frontogenesis & waves
5 Kata cold front
8 Circulation & frontogenesis
26 PV & WV imagery
3 Detached warm front
25 Tropopause folding
2 Warm front bands
24 PV & cyclogenesis
12 Three conveyor belt model
Commonly observed & familiar concepts
More advanced dynamics & recent developments
% 0 5 10 15 20 25 30 35 40
(b)
% of forecasters who indicated that they don't think a particular conceptual model is sufficiently correct given that they have come across and understand it.
26 PV & WV imagery
20 Frontogenesis & waves
25 Tropopause folding
8 Circulation & frontogenesis
15 Cyclogenesis life-cycles
22 Upper baroclinic waves
28 Orographic cyclogenesis
23 Straight jet streak models
4 Ana cold front
19 Petterssen vorticity
24 PV & cyclogenesis
5 Kata cold front
21 Stable & unstable waves
27 Spanish plume
9 Left jet exit intensifying front
10 Fronts at cloud edges
17 Comma cloud
16 Explosive cyclogenesis
11 Two conveyor belt model
18 Instant occlusion
6 Split-front evolution
14 Keyser/Shapiro model
3 Detached warm front
12 Three conveyor belt model
7 Classical occlusion
2 Warm front bands
1 Classical warm front
13 Norwegian cyclone model
% 0 5 10 15 20 25 30 35 40
(c)
% of forecasters who indicated that they don't have the diagnostics available to use a particular conceptual model given that they have come across it.
13 Norwegian cyclone model
15 Cyclogenesis life-cycles
28 Orographic cyclogenesis
14 Keyser/Shapiro model
17 Comma cloud
18 Instant occlusion
23 Straight jet streak models
19 Petterssen vorticity
27 Spanish plume
21 Stable & unstable waves
16 Explosive cyclogenesis
11 Two conveyor belt model
22 Upper baroclinic waves
7 Classical occlusion
4 Ana cold front
1 Classical warm front
20 Frontogenesis & waves
6 Split-front evolution
5 Kata cold front
3 Detached warm front
10 Fronts at cloud edges
9 Left jet exit intensifying front
12 Three conveyor belt model
2 Warm front bands
8 Circulation & frontogenesis
26 PV & WV imagery
24 PV & cyclogenesis
25 Tropopause folding
A
B
C
0 5 10 15 20 25 30 35 40
%
(d)
% of forecasters who indicated that a conceptual model does not add value to NWP given that they have come across and understand it.
27 Spanish plume
10 Fronts at cloud edges
12 Three conveyor belt model
26 PV & WV imagery
16 Explosive cyclogenesis
9 Left jet exit intensifying front
25 Tropopause folding
5 Kata cold front
4 Ana cold front
18 Instant occlusion
19 Petterssen vorticity
13 Norwegian cyclone model
17 Comma cloud
11 Two conveyor belt model
28 Orographic cyclogenesis
6 Split-front evolution
7 Classical occlusion
23 Straight jet streak models
22 Upper baroclinic waves
14 Keyser/Shapiro model
2 Warm front bands
1 Classical warm front
20 Frontogenesis & waves
3 Detached warm front
24 PV & cyclogenesis
15 Cyclogenesis life-cycles
8 Circulation & frontogenesis
21 Stable & unstable waves
More value
Less value
0 5 10 15 20 25 30 35 40

Figure 5

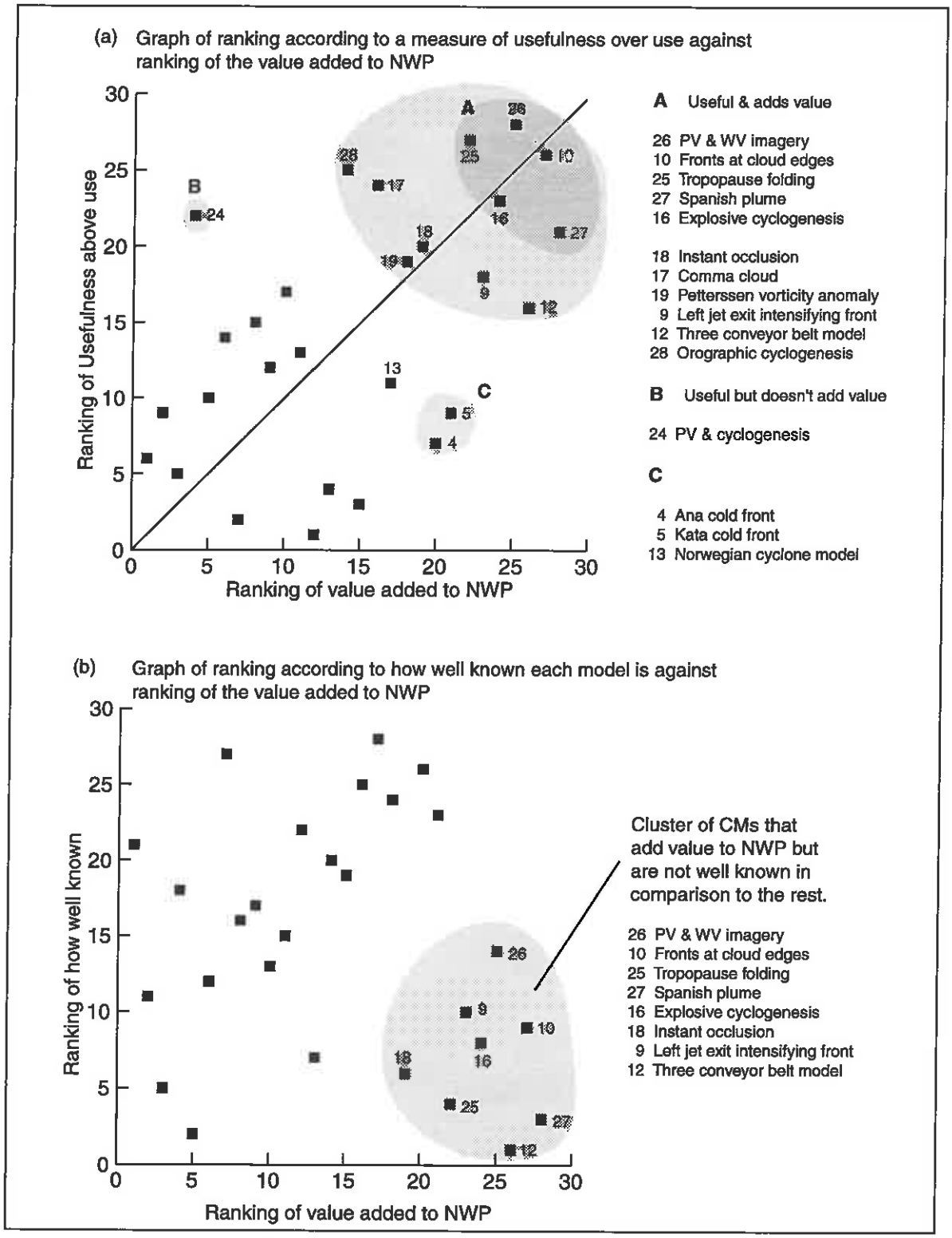


Figure 6

Cluster B: There is more of a problem with the availability of relevant diagnostics. Between 15 and 25% of respondents indicate a problem in this area. These CMs are mostly associated with frontal scales. The resolution of NWP models may not be adequate to resolve frontal scale features.

Specialised diagnostics, such as Q-vectors are often not available. Mesoscale rather than synoptic-scale features in satellite or radar imagery have to be considered.
Cluster C: These CMs have the largest problem with availability of diagnostics. They all concern PV and PV is not so widely available as a diagnostic. Water vapour imagery is not as easy to interpret as infrared or visible as well as not being so widely available to forecasters.

3.8) Added value to NWP (figure 5(d))

This is perhaps one of the most useful measures of the benefit of applying CMs in the forecasting environment since the aim is to produce the best possible forecast. Some useful information can be gleaned from this bar chart. A significantly high percentage of respondents have reservations about a good proportion of the CMs adding value to NWP output. The models which are thought to add the least value to NWP tend to be the more theoretical concepts for which the NWP diagnostics cannot readily be compared directly with observations. The models that come out best are the ones that put 'weather' into the phenomena e.g. 'Spanish plume' or 'Fronts at cloud edges' or the ones that can be used to diagnose problems with an NWP analysis field e.g. 'PV and WV imagery' or 'Explosive cyclogenesis'. Interestingly, most of the models which come out best as adding value to NWP are among the least well known and least used. This suggests that, so far, an opportunity has been missed to increase/publicise the usage of these models.

3.9) A measure of the best CMs (figure 6)

A measure of the best CMs should combine usefulness with value added to NWP. The measure of the usefulness of a CM compared to how much that CM is used, as discussed in section 3.3, is adopted here. All of the CMs are ranked in order of this measure of usefulness; 28 points for the most useful down to 1 for the least useful, and ranked in order of value added to NWP (figure 5d); 28 points for the most value down to 1 point for the least. The ranking for usefulness plotted against the ranking for value to NWP is shown in figure 6a. It is reassuring to see that there is a correlation between usefulness and value added, although with a large spread. Shaded area 'A' highlights the cluster of the 'best' CMs, i.e. those that are most useful and add most value to NWP.

It is appreciated that this method for determining the 'best' CMs has drawbacks.
The measure of usefulness over usage tends to favour the less well-used CMs. For example, the 'Norwegian cyclone model' is so well used that even if all respondents found it useful this measure of %useful - %use would still be small. The ranking method is very simple and spreads out the CMs evenly without taking into account the actual percentages of the responses. A CM may be ranked 15 places above another but only different by 1% of respondents. These concerns have been addressed by using the actual percentage responses and adding a scaling factor to compensate for the advantage to the less well used CMs. Although the new graph (not shown) arising from this alternative approach is slightly different, the important cluster 'A' is still preserved. An advantage of the ranking approach is that it prevents analysis of fine detail and extraction of more information than actually exists from a sample comprised of subjective replies. It should be noted that the assessment of each CM is relative to the other CMs, it is not an absolute measure of the value of the CMs.

Shaded areas 'B' and 'C' are also of interest. Area 'B' highlights the 'PV & cyclogenesis model' as being useful but not adding value to NWP. This may seem strange, but it is understandable that such a model can give dynamical insight without necessarily adding extra information to the NWP output. Area C seems to point to CMs that add value to NWP and yet are not useful; this is purely an artifact of the ranking method - these points move towards the line when using the more rigorous approach.

Figure 6b shows CMs ranked in order of how well they are known against the ranking for adding value to NWP. The shaded region contains the CMs that are perceived to add the most value to NWP

and yet are also the least known about. All the CMs in this cluster are within cluster 'A' in figure 6a. The clear impression conveyed is that many of the 'best' CMs are only known about by a small proportion of forecasters.

3.10) Additional comments from forecasters

A wide variety of additional comments about the CMs were included in the response to the questionnaire. The comments were a combination of replies to **Q4** (Figure 2) and general comments. Many fell into the broad categories highlighted below.

No reservations about using many of the CMs

CMs are taken for granted as a standard forecasting tool

Usage can be limited by the available diagnostics - covered in section 3.7

CMs can be over simplistic - this comment was made in particular for the Norwegian Cyclone model (13). However, it could be argued that it is the simiplicity of this CM which has allowed it to stand the test of time and apply to a wide range of systems. Newer, more complex forms of frontal analysis e.g. Shapiro (model 14) may better describe the meterolology of the event but are too complex for most external customers. Over-complexity of CM's may render them too case-specific and therefore not sufficiently general for easy use in forecasting.

Timing of developments can be a problem - there are problems in using various CM's for timing onset of weather events in quickly developing situations. Examples include forecasting when/if the release of potential instability will lead to deep convection at an individual site associated with a split-front (models 5 & 6) or left-exit event (model 9) or the onset of thunderstorms in a Spanish Plume (model 27).

Component approach - Several CMs involve the interaction of a number of different components e.g. during cyclogenesis, the dry intrusion and moist conveyor belt configuration varies from case to case. There is a continuum of models as opposed to discrete models (relates closely to Semple 1998). Many examples are "hybrids" and clear examples are the exception.

Some CMs require a great deal of experience and practice to apply - e.g. PV and WV imagery

CMs can constrain thinking - each event is different - it is the departures from the "clean" or idealised cases that are important for day-to day forecasting.

CMs can be useful for understanding, but not so useful for real-time forecasting

Some CMs have a geographical dependence

There can be an overlap between CMs - more than one CM can apply to a given situation. For example, development of fronts at cloud and precipitation edges (model 10) could be interpreted in some cases as a type of split-front evolution; classical occlusions could also be split fronts; frontal models usually fall into a subset of cyclogenesis life-cycles.

4.1) Conclusions and recommendations

The questionnaire has been successful in obtaining useful information about the understanding and application of CMs in the forecasting environment.

There is a large spread in knowledge and usage of the CMs chosen for the questionnaire. Most of the CMs are used by around half of the forecasters that know about them. They are generally regarded as being useful if they are used.

Many of the CMs are neither well-known nor understood, despite the likelihood that the forecasters who replied to the questionnaire are among the most keen and knowledgeable. The limited number of CMs that are well used could imply over reliance on NWP (or a perception that CMs are not useful). This may represent a lost opportunity to add value to NWP and perhaps raises questions about the role of the forecaster.

The older, more traditional CMs are the best known and most used. Examples are the 'Norwegian cyclone model' and the 'Classical warm front'.

There is very little criticism of the correctness of most models. This is a positive result if it indicates that the CMs do correctly describe phenomena, but of concern if it means that forecasters have insufficient understanding to feel confident enough to criticise the models. Unfortunately, the questions asked do not allow a separation of these possibilities.

Many of the CMs that are found to add the most value to NWP and are also the most useful are the least well known. Examples are the 'Spanish plume', 'Explosive cyclogenesis', 'Fronts at cloud edges', 'Tropopause folding' and the 'Three-conveyor belt' models.

The lack of appropriate diagnostics limits the usefulness of some CMs, especially those relating to frontal scales and potential vorticity. Examples are 'PV and cyclogenesis', 'Tropopause folding' and 'Warm front bands'.

Knowledge of some CMs is concentrated strongly in one country. Examples are 'Spanish plume' and 'Split-front evolution' (UK), 'Tropopause folding' (France) and 'Fronts at cloud edges' (Germany).

Questionnaires can result in as many new questions being raised as the ones that were answered. This is no exception; with the benefit of hindsight, modifications to some questions or different questions may have been more appropriate. It would have been interesting to find out exactly how CMs are used by forecasters and not just whether they are used. It would also be useful to find out why the correctness of the CMs is questioned so little. However, too many questions would have deterred many from replying, so in that respect a good balance was reached.

4.2) Recommendations

There are significant opportunities for training forecasters in the use of CMs. This could be achieved by:

- Exploiting existing training software such as SATREP and other packages developed within EUROMET.
- Regular discussions on the choice of CMs in real situations, possibly in the working group of European forecasters.
- Providing easily-accessible explanatory material on how individual CMs can be used operationally by the forecaster. Individual countries could be encouraged to contribute to a common reference set of useful existing cases or new cases as they arise.
- Publicising the least well known or frequently used CMs that are perceived to add value.

Essential diagnostics are often not available, limiting the use of CMs. Consideration needs to be given to efficient workstation displays of appropriate NWP diagnostics and observational data to facilitate

usage of CMs. A recommended set of the meteorological fields that are required for each CM could be very useful.

Further work is recommended on major areas such as the use of WV imagery and the 'Spanish Plume' (and others) which are thought to have considerable potential. Future research is needed to produce refined CMs adapted for different parts of Europe and to properly assess the validity of these models and the value added to NWP.

If CMs are considered to add value to NWP, techniques to incorporate information contained in CMs directly into NWP models should be proposed and developed.

Acknowledgements

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Thanks to all the forecasters who replied to the questionnaire and special thanks to the representatives from each country who distributed copies and passed on the completed questionnaires.

REFERENCES

COST-78 Phase 1 report : Nowcasting - a survey of current knowledge, techniques and practice.

Semple A.T. 1998 Conceptual models of cyclogenesis. JCMM Internal Report 92.

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